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LeRC REDUCED GRAVITY FLUID MANAGEMENT
TECHNOLOGY PROGRAM

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LeRC REDUCED GRAVITY FLUID MANAGEMENT TECHNOLOGY PROGRAM

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ABSTRACT

A survey is presented of the reduced gravity fluid management technology program sponsored by the Lewis Research Center (LeRC) over the past decade. The work was conducted both under contract and in-house. The in-house studies used scale model propellant tanks in drop towers that provided up to 5 seconds of reduced gravity test time. Most of the program effort yielded information on the solution of reduced gravity fluid management problems in general with a few studies pointed specifically at the improvement of the Centaur vehicle.

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These studies at the LeRC are now shifting from the utilization of in-house experimental facilities to the development of Spacelab experiments. The Cryogenic Fluid Management Experiment, currently undergoing detailed design, will provide an orbital evaluation of a subcritical liquid hydrogen storage and supply system as part of the Shuttle/Spacelab program. An experiment to study orbital transfer of liquids and a Spacelab facility capable of housing multiple fluid dynamic and heat transfer experiments are presently being planned. Contractual efforts are continuing to analytically evaluate propellant management systems for both low and high thrust Orbit Transfer Propulsion Systems and to develop computer techniques for simulating reduced gravity fluid dynamic processes.

INTRODUCTION

Approximately 20 years ago the Lewis Research Center (LeRC) initiated a research program intended to provide the technology base for the design and operation of fluid systems in the reduced gravity environment of space. The early emphasis of this program involved the use of small transparent tanks and the LeRC drop tower to experimentally study the behavior of liquid-vapor interfaces in response to changes in gravity level, disturbances and liquid draining from the tank. Particular attention was placed on identifying dimensionless parameters which characterized the fluid phenomena observed and allowed the prediction of fluid behavior in full size spacecraft tankage.

During the early 60s the Centaur vehicle development effort was transferred to the LeRC. In support of this project, experiments were conducted to assist in the improvement of the Centaur; specifically, studies of propellant sloshing, settling and draining in Centaur configuration tank models were undertaken. Also, the use of cryogenic propellants, liquid hydrogen and oxygen, in the Centaur vehicle triggered an interest in the improvement of thermal control systems both for the Centaur and for advanced chemical propulsion systems. Both in-house and contractual efforts were initiated to develop filament wound feed lines and tank supports, multi-layer insulation, shadow shields, light-weight vacuum jackets and tank pressure control techniques.

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The LeRC reduced gravity fluid management program was subsequently enhanced by the construction of the Zero-Gravity Facility which increased the available test time from 2.2 to 5.1 seconds. The experimental program was expanded to include studies of liquid-vapor interface configuration, sloshing and settling in a variety of tank sizes and shapes. In addition, liquid flow into tanks, the use of baffles to reduce liquid residuals during outflow boiling, venting, bubble motion and the impingement of gas jets on liquid surfaces were experimentally examined.

In May 1974 the LeRC initiated a contract with General Dynamics Convair to perform a "Low-G Fluid Transfer Technology Study." The first task of this effort involved an extensive literature search, screening, and compilation of document summaries in the areas of low-g fluid behavior,² cryogenic thermal control,³ and fluid management systems.⁴ Approximately 40 percent of the documents summarized describe work either performed at or sponsored by LeRC. This paper presents a review of the LeRC reduced gravity fluid management program using these document summaries as a starting point.

The current emphasis of the LeRC program and, thus, the emphasis for this paper, is directed toward the development of technology for the design of fluid management systems including liquid acquisition, thermal control of cryogenic tankage and fluid transfer. This is not intended to be an exhaustive review but rather a broad treatment to acquaint the reader with the LeRC fluid management program and the general state-of-the-art. Many of the references cited contain extensive bibliographies with which particular subjects may be pursued in more detail.

LIQUID ACQUISITION

The obvious starting point for any study of liquid acquisition or positioning is an understanding of low-g fluid behavior. The low-g fluid behavior technology area is adequately summarized in reference 2 with the exception of the recent mathematical and computational work of Dr. Paul Concus. These studies provided an analytical prediction of liquid-vapor interface configuration,⁵ stability⁶ and a software package for calculating axisymmetric liquid-vapor interface configuration as a function of container shape and acceleration environment.⁷

The objective of the liquid acquisition portion of the LeRC fluid management program is to develop the technology necessary for positioning liquid and vapor within a tank in reduced gravity to enable liquid outflow or vapor venting. Liquid acquisition techniques can be divided into two general categories:

1. Active liquid acquisition by the creation of a positive acceleration environment resulting from the propulsive thrust of small rocket engines.
2. Passive liquid acquisition utilizing the liquid capillary forces by using solid baffles or liquid traps made of fine mesh screen material.

ACTIVE - PROPULSIVE SETTLING

Most NASA liquid propellant upper stages have used or are using settling rockets to position propellants prior to venting or main engine start. The

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criteria for sizing the settling rockets was based on early drop tower programs that studied liquid-vapor interface stability and liquid settling phenomena.^{8,9} Reference 9 established that liquid rebounding or geysering and liquid circulation can occur during the settling process causing very low rates of liquid collection. A later experimental program¹⁰ using scale model Centaur tanks simulated the real vehicle acceleration environment and established liquid settling times as a function of the tank fill level. A numerical code utilizing the marker and cell technique¹¹ has been developed to simulate both settling of propellants by intermittent thrust and continuous thrust in the Centaur vehicle.

The large safety factors generally applied to the selection of settling rocket thrust level and duration yield corresponding large hardware and propellant weight penalties. Utilizing an existing empirical analysis and data obtained from earlier LeRC drop-tower programs, Sumner¹² developed estimates of the minimum velocity increment required to achieve liquid reorientation. The results of this study indicate that significant reductions in the weight penalties associated with propulsive settling could be realized; however, additional experimental verification of the analysis should be undertaken prior to utilizing this technique for vehicle design. Present plans call for an experiment which will generate this data to be included in a Spacelab facility.

PASSIVE - SCREEN DEVICES

The idea of using the liquid retaining property of fine mesh screen materials (Fig. 1) to position liquids in a reduced gravity environment was introduced in the early 1960s. The first use of screen materials for liquid acquisition was to cover the propellant sump at the bottom of propulsive vehicle tanks. The liquid trapped in the sump was used to provide on-orbit engine restart capability regardless of the bulk liquid position in the tank. Once the engine ignited, the resulting thrust settled the propellants refilling the sump and allowing continued engine firing. This general class of liquid positioning device is commonly referred to as a partial acquisition system or start basket.

For applications that require continuous feed of liquids under reduced gravity conditions, it is necessary to design the liquid acquisition device so that it contacts the liquid bulk no matter where the liquid is positioned in the tank. These acquisition devices generally consist of a complete screen liner or multiple channels, generally with screen on one side, which are positioned circumferentially inside the tank. This general class of liquid positioning device is commonly referred to as a total communication system.

Screen Characterization. Although screened sumps performed their intended function flawlessly, a general lack of design information existed for more complicated liquid acquisition device geometries. During the early 1970s the LeRC initiated a program to establish fine mesh screen-liquid interaction characteristics with emphasis on extending the available design information to include the cryogenic liquids hydrogen and oxygen.

The liquid retention capability of fine mesh screen materials is experimentally determined by measuring the resistance of the wetted screen to

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penetration by vapor, commonly referred to as the screen bubble point. The screen bubble point is the pressure differential that must be applied across the wetted screen material to cause vapor to penetrate into the liquid acquisition device and thus destroy its liquid retention capability.

In order to successfully design fine mesh screen liquid acquisition systems, it is necessary to account for all the sources of pressure differential between the inside of the acquisition device and the surrounding vapor. The objective of this analytical accounting procedure is to insure that most of the liquid can be removed from the tank prior to penetration of the screen material by vapor bubbles. The pressure differential across the screen results from the sum of the hydrostatic head in the reduced gravity environment, the liquid flow losses within the screen acquisition device and the flow loss through the screen material, and from external sources; for example, pressure variations caused by vibration.

The first study in this area supported by the LeRC¹³ established the bubble point and flow losses both parallel and perpendicular to a variety of fine mesh screen materials using liquid hydrogen as the test fluid. Reference 13 also contains an extensive catalog of types and suppliers of fine mesh screen materials. The program was later expanded to establish the effect of transient liquid flow, such as would result from opening and closing valves in the outlet lines, on the liquid retention characteristics of screen materials.¹⁴ The effect of vibration on the liquid retention characteristics of screen materials was experimentally established as reported in reference 15.

An interest in the fluid dynamic phenomena associated with the refilling of start baskets following engine ignition led to both experimental¹⁶ and analytical¹⁷ studies of liquid jet impingement on screen materials. These two studies served as building blocks for the experimental evaluation and analysis of the refilling of a capillary device with settled fluid. The net result of this work was the development of a computer program, based on the successful correlation of the test data, that provides a useful start basket design tool.¹⁸

The interest in cryogenic propellants adds an additional consideration to start basket design. For cryogenic liquids, heat addition to the propellant tank and ultimately to the liquid acquisition device is inevitable during prolonged orbital coast. Reference 19 presents the experimental results of a program which determined the degradation of the liquid hydrogen bubble point for a variety of screen materials and heat fluxes; very little bubble point degradation was observed for heat fluxes up to 3000 Btu/hr-ft². However, these tests were conducted with the screen material in direct contact with the liquid bulk on one side. Start baskets designed for cryogenic liquids will often have portions of the screen surface of the device exposed to vapor on both sides. Since evaporation will take place from the screen surface, the ability of the screen material to stay wet by wicking liquid from those portions of the device in contact with the liquid bulk becomes important. The wicking characteristics of screen materials²⁰ and multiple screens in combination with support materials²¹ have been experimentally established and analytically correlated.

Start Baskets. During the past decade the Centaur vehicle has

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periodically been considered for inclusion in the Space Transportation System as a high performance upper stage to be used in conjunction with the Shuttle. As part of the study effort intended to identify required or desirable modifications to the Centaur, a comparison of propellant acquisition concepts was performed.^{21,22} The existing Centaur hydrogen peroxide settling system was compared with several passive liquid acquisition system concepts. Although the acquisition systems were specifically configured for the Centaur vehicle (Fig. 2), it is the author's contention that the general results of the study are applicable to any cryogenic upper stage of similar size. Specifically, the following conclusions were reached:

1. Start baskets are the most attractive passive liquid acquisition system concept.
2. Start baskets become more attractive than propulsive settling when multiple engine burns are required for a particular mission.
3. The use of cooling coils on start baskets to prevent screen dry-out yields prohibitive weight penalties. Liquid evaporated from the screen surfaces of a start basket must be replenished by providing adequate liquid wicking paths.
4. Use of start baskets rather than propulsive settling appears to be a viable option only if a heat exchanger, "subcooler", is used inside the start basket to provide the required engine feed system net positive suction pressure.

Total Communication Systems. Many potential applications for the on-orbit storage and supply of cryogenic liquids have been identified by NASA. In contrast to the start baskets previously discussed, total communication systems are required for applications where supply of the cryogenic liquid is always under reduced gravity conditions.

Trade studies were performed to evaluate alternate total communication system configurations which could be integrated with cryogenic thermal control systems.^{13,19} These studies led to the selection of two circumferential screen-channels to provide liquid acquisition and a vapor-cooled-shield for thermal control. A more detailed discussion of cryogenic thermal control systems appears in the following section.

Using the screen-channel/vapor-cooled-shield concept, the McDonnell Douglas Corporation performed a preliminary design of the Cryogenic Fluid Management Experiment (CFME)²³ which is a part of the Shuttle/Spacelab program. The specific objectives of this experiment are:

1. To determine the ability of a thermal control system to isolate a screen acquisition system from heat addition (vapor formation).
2. To determine the performance of a thermal control system in controlling tank pressure during extended storage periods.
3. To determine the effects of outflow rate and pressurization mode on the ability to provide liquid on demand.

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4. To obtain engineering data suitable to establish design criteria for subcritical cryogenic liquid storage and supply systems.

5. To evaluate reduced gravity liquid quantity gaging devices.

The detailed design, safety review and test program planning for the CFME (Fig. 3) are currently being conducted by the Martin Marietta Corporation under LeRC Contract NAS3-21591.

THERMAL CONTROL

This portion of the LeRC fluid management program has as its objective the development of the required technology for the efficient design of thermal control systems for cryogenic tankage. A complete program would include evaluations of insulation systems, heat exchangers and pressure control devices. In the past the LeRC was involved in the development and evaluation of insulation systems. The current LeRC program is primarily concerned with developing pressure control system technology with special emphasis on thermodynamic vent system concepts.

MULTILAYER INSULATION

Multilayer insulation (MLI) systems composed of alternate layers of reflective foil and low conductivity spacer material have proven to be highly effective in minimizing heat addition to cryogenic tankage in the high vacuum environment of space. NASA's interest in developing a high performance, reusable cryogenic upper stage to be used in conjunction with the Shuttle has introduced concerns about the durability and reusability of MLI.

A recent paper by Sumner and Barber²⁴ provides a comparison of three "Reusable Insulation Systems for Cryogenic Earth-Based Space Vehicles." Two of the insulation systems were MLI while the third utilized hollow-glass-microspheres. One of the MLI systems, utilizing double-aluminized mylar for the radiation shields, was designed, assembled and tested at the LeRC. The effects of repeated thermal cycling and estimates of insulation system weight, when optimized for a typical space mission, are presented for the three insulation systems. The two MLI systems had significantly better thermal performance and lower weight than the microsphere system. The MLI system tested at the LeRC initially had a slightly greater effective thermal conductivity than the other MLI system, but showed significantly less performance degradation due to thermal cycling.

PRESSURE CONTROL

Direct Venting. The simplest technique for controlling cryogenic tank pressure is to install a vent line in the top of the tank and bleed off vapor as required. However, in space, with the absence of gravitational forces to separate the higher density liquid from the vapor, it is generally impossible to determine where the vent line should be installed.

Reference 25 presents the results obtained from a venting study conducted in the LeRC Zero Gravity Facility where only capillary forces were available for positioning the liquid. As can be seen in Figure 4, the

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absence of any gravitational force causes problems even though vapor is initially vented from the tank. As the tank pressure decreases, boiling takes place in the bulk liquid region; the resulting vapor bubbles expand and push the liquid toward the vent. Ultimately, the undesirable condition of dumping liquid would result.

For propulsive vehicles like the Centaur, the same settling rockets that are used to acquire propellants for on-orbit engine restart can be used to position the propellants prior to venting. This technique has the disadvantage of utilizing settling rocket propellant for each vent cycle, thus reducing the vehicle's payload placement capability. Cryogenic tanks which have screen liquid acquisition systems cannot utilize direct venting for pressure control since only a portion of the liquid is contained in the acquisition device with no control over the remainder of the liquid contained within the tank.

Thermodynamic Vent Systems (TVS). Efforts to improve the performance of propulsive stages and allow the use of screen systems in cryogenic tankage have introduced the concept of the thermodynamic vent system. TVS concepts are particularly attractive when cryogenic payloads for the Space Shuttle are considered. Under many normal operating conditions and all abort modes, payload requirements cannot dictate Shuttle operations so settling to relieve tank pressure would be impossible. Thermodynamic vent systems should impose no operating constraints on the Space Shuttle.

In the TVS a small amount of the cryogenic liquid is sacrificially evaporated to offset the unavoidable heat addition to the tank. Cryogenic liquid is withdrawn from the tank and passed through a Joule-Thompson valve with a resultant pressure and temperature reduction. This cold two-phase fluid is then introduced into a heat exchanger where evaporation continues and heat absorption takes place before the resulting vapor is vented overboard.

The heat exchanger is typically located either within the tankage insulation (vapor cooled shield) or inside the tank. In the first option, most of the incoming heat is intercepted before it reaches the liquid contained in the tank. In the second option, the cryogenic liquid and vapor in the tank are the heat exchanger hot side fluid. This fluid is cooled during operation of the TVS, thus controlling the tank pressure.

For the large cryogenic tankage typical of high performance upper stages, the heat exchanger in the tank should have a lower weight than a vapor cooled shield. However, this option introduces the additional requirement of circulating the fluid in the tank so that effective cooling can take place.

Two experimental studies were conducted in the LeRC Zero-Gravity Facility to examine the effect of reduced gravity on the fluid circulation patterns in spherical²⁶ and cylindrical²⁷ tankage. Axial liquid jets were used to provide mixing of the liquid bulk or circulation of the simulated propellant over the tank walls. In addition to these two desired liquid flow patterns, two undesirable liquid flow patterns were observed; geyser formation and liquid collection at the end of the tank opposite the jet exit (Fig. 5). The transitions between the four flow patterns were a function of the tank geometry, the liquid-jet velocity, the volume of liquid in the tank and the location of the tube from which the liquid jet exited.

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Both TVS heat exchanger location options were considered during the cryogenic liquid storage and supply system trade studies.^{13,19} For cryogenic tankage like the CFME the pumps required for the internal TVS are extremely small. Because of concerns over the ability to fabricate these small pumps as well as their reliability and performance, the vapor cooled shield TVS concept was chosen for this size application. It was recently suggested that the random acceleration environment in the Shuttle cargo bay may eliminate the need for a pump with the internal TVS concept. Consequently, a reevaluation of thermodynamic vent system concepts for the Cryogenic Fluid Management Experiment is currently underway as part of LeRC Contract NAS3-21935.

FLUID TRANSFER

Over a period of many years, NASA has been producing the technology which will be necessary for the development of large orbit transfer vehicles and manned space platforms that would remain permanently in space. The need to periodically replenish the liquid supply systems on these vehicles and spacecraft led the LeRC, in the early 1970s, to include on-orbit fluid transfer as a part of the reduced gravity fluid management program. The specific objective of this portion of the program is to develop the technology to permit efficient transfer of liquids from a supply tanker to a receiver vehicle or spacecraft while in the reduced gravity environment of space.

The "Low-G Fluid Transfer Technology Study",^{28,29} mentioned earlier, provided conceptual designs of supply tankers for the on-orbit fueling of an orbit transfer vehicle, the in-space resupply of another Shuttle Orbiter and the orbital resupply of a variety of spacecraft. These potential supply tanker designs were used to help identify technology gaps and system characteristics critical to both cryogenic and noncryogenic on-orbit fluid transfer. The potential problem areas identified included chilldown and subsequent filling of cryogenic receiver tanks without excessive liquid loss or pressure rise, filling of noncryogenic receiver tanks without excessive pressure rise or liquid loss and the complete filling of fine mesh screen liquid acquisition devices.

TANK DRAINING

Two experimental and analytical studies of reduced gravity draining from cylindrical tanks were recently completed at the LeRC. The first of these studies³⁰ provides an analytical correlation of the experimental data which relates liquid residuals to the outflow rate and acceleration environment for hemispherically bottomed tanks. The second study³¹ presents experimental verification of an analytical technique which was developed to indicate how tank outlets should be shaped or contoured in order to minimize liquid residuals. The contouring analysis was applied to the design of tanks that could be used for the on-orbit fueling of a cryogenic orbit transfer vehicle; the resulting contoured outlet dimensions for three combinations of acceleration environment and fluid transfer time are shown in Figure 6. Another recent analytical and experimental study was conducted at the LeRC to establish minimum liquid hydrogen levels required to prevent vapor ingestion in the feed line when restarting the Centaur engines in space.³²

Several contractual efforts have been sponsored by the LeRC to develop

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numerical techniques to study the reduced-gravity tank draining phenomena.³³⁻³⁵ The last of these three studies resulted in the development of an exportable computer program utilizing the marker and cell technique which has been installed on the LeRC Univac 1100 computer. Excellent agreement between the experimental results of reference 30 and the analytical results of reference 35 has been achieved. Although the current capability of this reference 35 program is restricted to simulation of reduced-gravity tank draining phenomena, the basic analytical and computational method employed has the potential for being applied to a wide variety of fluid dynamic problems.

RECEIVER TANK FILLING

Two analytical studies of the on-orbit filling of tanks containing fine mesh screen total communication systems were completed in 1978. These two parallel studies differed in the proposed technique for filling tanks on-orbit and, thus, present different analytical solutions to the problem. Reference 36 analyzed a filling technique based on maintaining separation of the liquid and vapor phases within the receiver tank during the entire fill process. This technique allows direct venting from the vapor region to maintain acceptable tank pressure; however, extremely low liquid transfer flow rates are required in order that the stability of the liquid-vapor interface is maintained. In contrast to the above "fluid dynamic" technique, reference 37 presents the analysis of a "thermodynamic" technique for the on-orbit filling of receiver tanks. The thermodynamic filling technique is based on the concept of alternately chilling and venting cryogenic tankage until the receiver tank is cold enough that the tank can be filled without venting. Pressurization following tank filling will subcool the bulk liquid and condense any vapor bubbles trapped in a fine mesh screen liquid acquisition device. Noncryogenic tanks can also be filled without venting if relatively high pressure levels can be tolerated by the tanks. The thermodynamic filling technique analysis has recently been extended to include consideration of much larger propulsion vehicle tankage.³⁸

CONCLUDING REMARKS

IN-SPACE EXPERIMENTATION

During the 1970s the level of effort devoted to the LeRC in-house reduced gravity fluid management technology program has steadily declined. This decline can be partially attributed to NASA's reduced work force, but primarily resulted because meaningful research that can be conducted within the experimental size and test time limitations imposed by ground based facilities was nearly exhausted. The emphasis of the LeRC program is now directed toward the development of payloads for the Shuttle/Spacelab where larger experiments can be utilized and days of test time are available.

A Spacelab "Two-Phase Fluid Research Facility" is currently being conceptually designed by the General Dynamics Corporation under LeRC Contract NAS3-21750. This facility will be designed to accommodate a variety of experiments intended to examine both fluid dynamic and thermodynamic reduced gravity physical phenomena. Specifically, for the first flight of this facility, experiments will be incorporated to study propellant settling fluid dynamics, pool boiling heat transfer and two-phase forced convection boiling

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for application to heat exchanger design.

Two fluid transfer experiment conceptual designs are currently being prepared under contract to the LeRC. The two designs differ primarily in size; one will nearly require a dedicated Shuttle flight (General Dynamics/NAS3-21935) while the second experiment can be accommodated on a single Spacelab pallet (Beech Aircraft/NAS3-22260). The pallet experiment is presently envisioned to incorporate the Cryogenic Fluid Management Experiment discussed earlier as the test fluid supply tank and has been designated the "In-Space Cryogenic Fluid Management Technology Facility" (Fig. 7). In addition to the previously discussed objectives of the CFME, this facility will provide engineering data and a capability demonstration for the transfer of cryogenic liquids, thermal control of both the transfer line and the receiver tank and liquid acquisition in the receiver tank following liquid transfer.

LOW-THRUST CHEMICAL PROPULSION SYSTEMS

Both NASA and DOD have forecast the need for large space structures to be placed in geosynchronous orbit. Deployment, assembly and checkout of these structures in the near vicinity of the Shuttle would allow manned intervention in the operations if operational difficulties should arise. However, low earth orbit to geosynchronous orbit transfer of the totally functional large space structure will require low engine thrust levels to preclude damaging the deployed structure. Low-thrust chemical propulsion systems offer the potential of meeting this payload transfer requirement while providing total trip times on the order of a few days.

These low-thrust chemical propulsion system concepts may require reduced gravity fluid management technology development in two areas: (1) thermal control of cryogenic propellants due to the long orbital storage times required and (2) propellant supply to the engines due to the low acceleration environment even under full thrust. The Martin Marietta Corporation is currently under contract (NAS3-21954) to the LeRC to provide a determination of total propellant requirements, an evaluation of insulation system concepts, a comparison of liquid acquisition techniques and an identification of technology requirements for low-thrust chemical propulsion systems. Current plans indicate that a major portion of the future LeRC reduced gravity fluid management program will be directed toward resolution of problems which might impede the development of a low-thrust chemical propulsion system.

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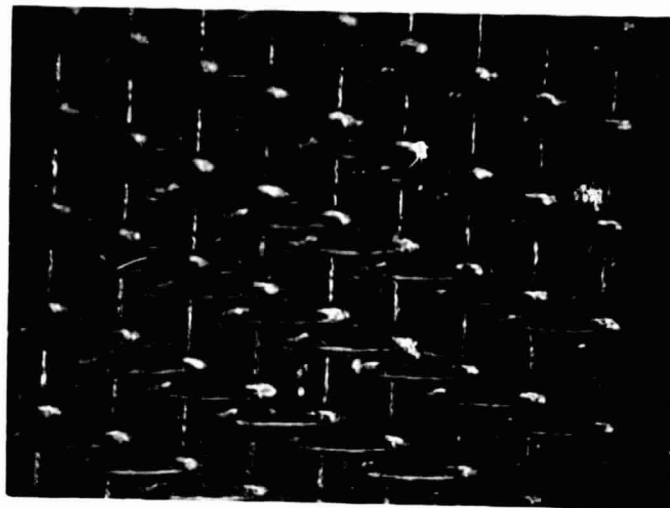


Figure 1. - 200x600 Twilled-weave dutch screen sample magnified 100 times.

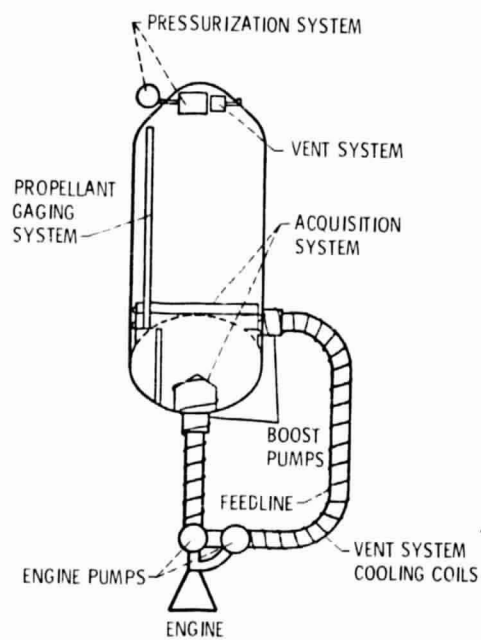
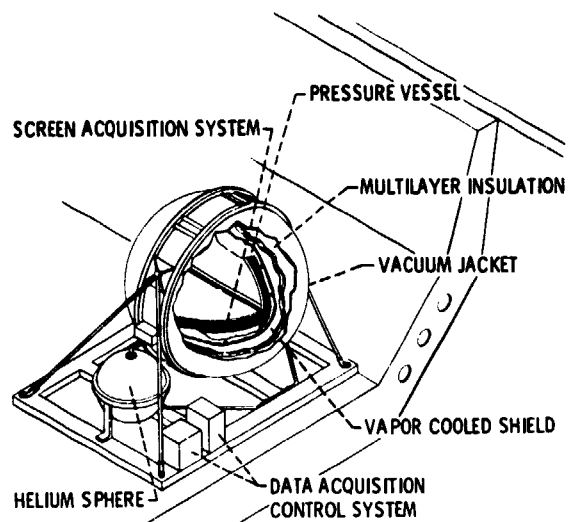


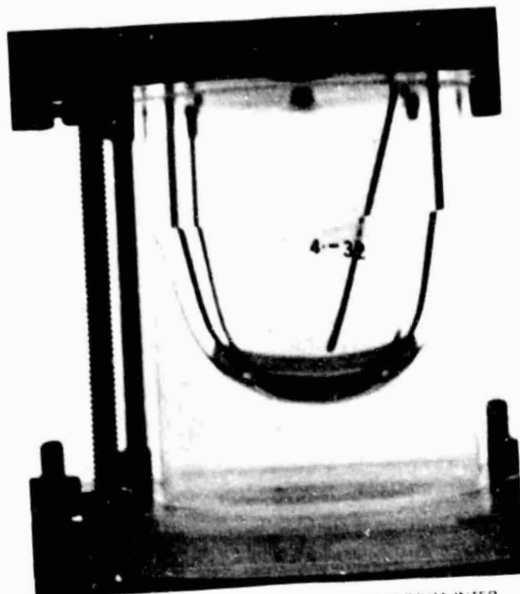
Figure 2. - Centaur liquid acquisition system interfaces.

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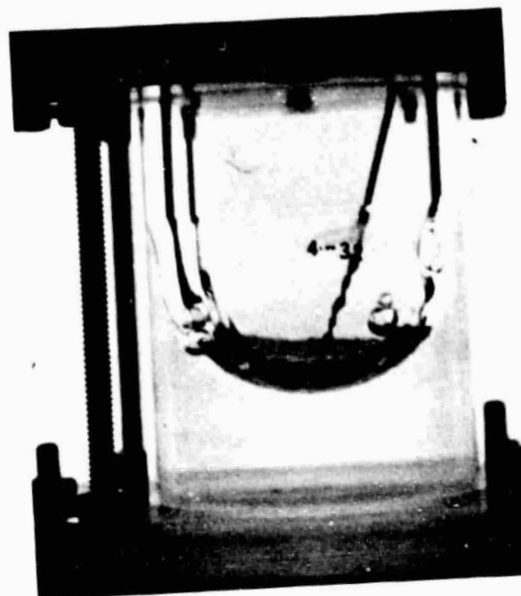


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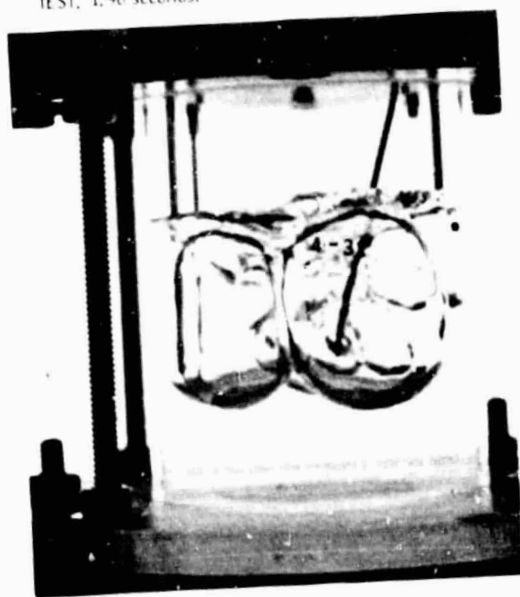
Figure 3. - Cryogenic fluid management experiment.



(a) FORMATION OF ZERO-GRAVITY EQUILIBRIUM INTERFACE. VENTING BEGINS. TIME FROM INITIATION OF TEST, 1.90 seconds.



(b) BOILING OCCURS NEAR LIQUID-VAPOR INTERFACE. TIME FROM INITIATION OF TEST, 2.70 seconds.



(c) VAPOR GENERATION INCREASES, INTERFACE RISES TOWARD VENT. TIME FROM INITIATION OF TEST, 4.00 seconds.



(d) CONFIGURATION PRIOR TO TERMINATION OF TEST. NO VENTING OCCURRING. TIME FROM INITIATION OF TEST, 5.17 seconds.

Figure 4. - Venting induced bulk boiling in zero-gravity. Test fluid, refrigerant C318. Average vent rate, 1.0 ullage volume per second.



(a) GEYSER FORMATION.



(b) COLLECTION ON AFT BULKHEAD.

Figure 5. - Axial liquid-jet flow patterns in zero-gravity.

SYSTEM	DIMENSION, m					
	A	B	C	D	E	F
SEPARATED FROM SHUTTLE - 10^{-4} g's; 2.5-hr TRANSFER	0.5	1.5	0.228	0.9	2.0	0.369
SHUTTLE DRAG - 10^{-6} g's; 10-hr TRANSFER			.354	.8		.572
SHUTTLE DRAG - 10^{-6} g's; 30-hr TRANSFER			.204	1.0		.329

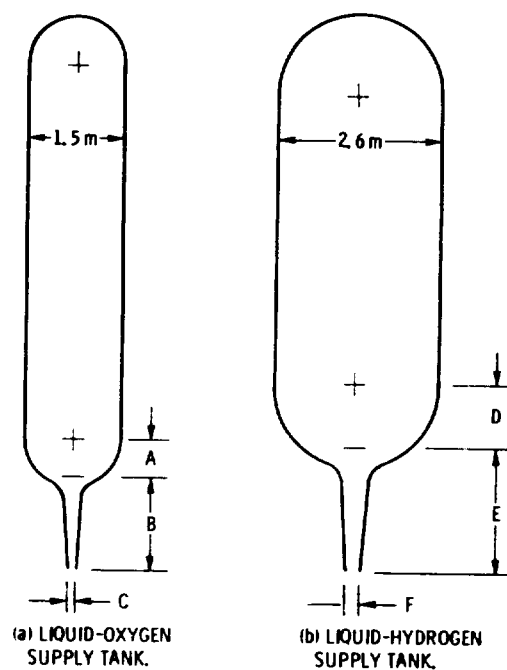


Figure 6. - Contoured-outlet tanks for OTV in-orbit supply system.

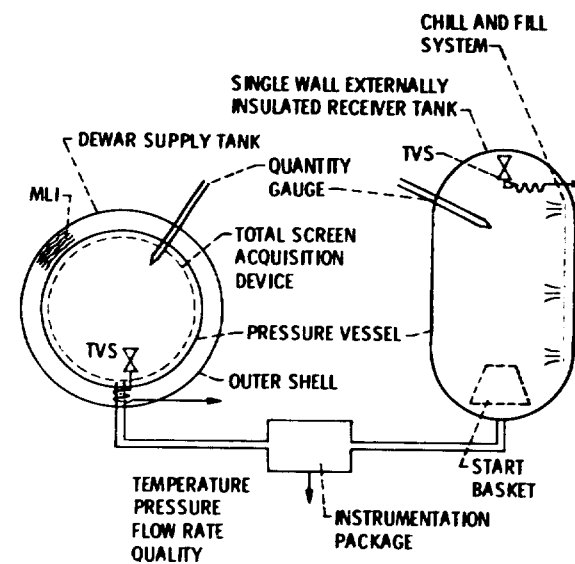


Figure 7. - In-space cryogenic fluid management technology facility.